OCEAN-LAND INTERACTION IN COASTAL ZONES AND EFFECT OF OCEAN-LEVEL CHANGE

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Contents

Summary

This article considers processes of physical (dynamic) interaction (fluvial, estuarine, and marine) between sea and river waters, their basic regularities and specific displays in various geographical regions. Descriptions and explanations are presented for the main natural phenomena related to sea-level oscillations in the circumlittoral zone due to astronomical, atmospheric, and tectonic reasons, as well as the resulting interaction process between land and ocean waters. Level oscillations by tides, storm surges, and tsunami waves are examined, their physical nature is interpreted, and quantitative features, geographical distribution data, and impact on coastal residents are presented. The role of level oscillations owing to wind set-up, and seiches is noted. The principal directions of future research of these natural phenomena are pointed out.

1. Classification of the interaction processes between sea and river water

In general, water interaction between ocean and lithosphere can be considered in global, regional, and local aspects, as described in *Water Exchange between Land and Oceans*. Global and regional interactions were discussed in this article, and the regularities of local interactions are the main task of the present article. First of all, it should be noted that local interaction is mainly between ocean water and river flow. Groundwater inflow is only few percent of surface water inflow, and unlike the later, is distributed relatively evenly along the shoreline of continents. At the same time we must note the extreme disparity in the size of fluvial and marine waters. Interaction Water Areas (IWA) vary from tens (small brooks) to thousands of kilometers (the largest rivers) and occur

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throughout nearly all the coasts of the world. Uniform shore lines, bays, fiords, lagoons, and estuaries, as well as direct river inflow and deltas, as are examples of interaction zones, depending on shoreline topography and contours. Therefore the degree of IWA isolation from the open sea determines either equality of marine and fluvial influences or predominance of one over the other.

According to the character of sea and river water interaction (SRWI), four main types may be distinguished: physical, chemical, geological, and biological interactions. In practice, all types are observed at the same time, but our focus here is mainly physical interaction regularities. All the relevant factors may be divided into natural and man-made. The former are fluviatile and marine factors, mixing processes, and physio-geographical factors. The most important among the fluviatile factors is river runoff. Its seasonal and inter-annual variations control the intensity and character of fluvial influence. In addition, the ice conditions in river estuaries and deltas have some effect on SRWI. Marine factors are much more varied. These include level oscillation, currents, wind driven waves, and salinity. Physio-geographical factors include on the one hand an extensive group of local conditions (shoreline contours, depth distribution, shelf and river delta features, tectonic movements, sediment transport, soil-plant cover, etc.), and, on the other hand, climate has a big influence. Finally, in the zone of contact between marine and fluvial waters, mixing processes lead to occurence of density driven circulation, small- and mesoscale turbulent and convective movements, and formation of fronts, and secondary water masses, etc.

As for the man-made factors, these are rather complex systems of water management measures and multipurpose projects. Anthropogenic factors can clearly have both direct and indirect effects on SRWI. Direct influence is related to water management projects, harbour construction, canals, dikes, breakwaters, etc. as well as to agriculture development and urbanization of river deltas and estuaries. Many of the largest cities of the world are situated on estuaries or river deltas. Indirect influences are related to water management activity in river catchments and is manifested as anthropogenic change of river runoff.

Physical (dynamic) SRWI processes may be divided into three types: fluviatile, estuarine, and marine (see Figure 1). *Fluviatile processes* are related to the conditions of river jet inflow to the sea. The quantity and annual pattern of river flow controls changes in levels and current velocity in the mixing and nearshore areas, the delta flooding character, and freshwater spreading distance, etc. Naturally, the extent of river runoff influence on SRWI is very uneven because of variation in depth and local topography. The influence is greater on gently shelving coasts than when deep water is close to the shore.

Fluvial jet energy is quickly dissipated as it runs into marine waters, and at the same time mixing processes are intensified, particularly due to tidal motion, wind, waves, and currents. This mixing creates a pressure field with horizontal gradients, and, as a result, to gradient-driven circulation. This circulation is the most important regularity of *estuarine type* SRWI**.** Estuarine circulation is noticeably affected by morphometric parameters, i.e. shoreline topography, contours, and depth distribution. On one hand, these parameters directly affect the circulation behaviour, and on the other, they have a

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major influence on dissipation of tidal energy. Approximate equality of fresh and sea water flows is typical of estuarine-type processes, but estuarine SRWIs are more variable than others due to complex interactions between coastal currents, gradient-driven circulation, and morphometric factors.

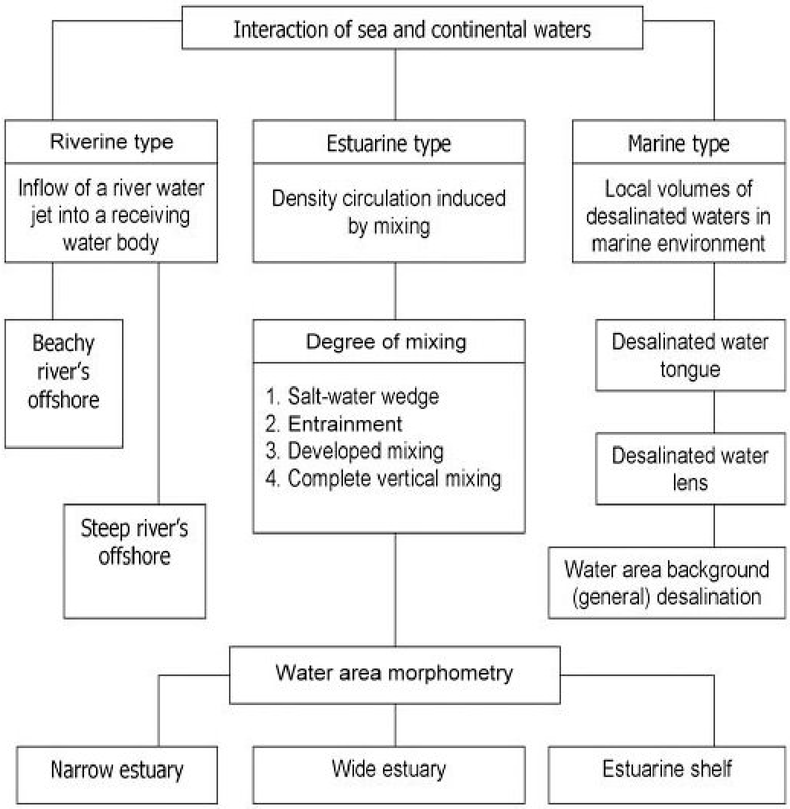

Figure 1. Classification of sea and land water physical interaction types.According to Pantyulin, A.N. (1982)

Bowden (1967) separated the typical modes of mixing in estuarine SRWI as follows: completely stratified (salt wedge), stratified with entrainment, moderately or well mixed, and completely mixed. Complete stratification occurs when river flow is predominant and the effect of mixing factors is weak. As a result, the offshore freshwater flow is situated above more saline water; the two layers are separated by a halocline. The lower layer is called a "salt-water wedge", and the upper a "freshwater wedge". In nature net two-ply flow is observed relatively rarely due to complicating factors: tidal motion capturing the whole water column, wind and internal waves, seiches, and others. A salt-water wedge is manifested very clearly in the River Mississippi estuary. This wedge extends up the main river channel for more than 300 km when river discharge is not large. Conversely, when the runoff is significantly greater than normal, the wedge is pushed out of the estuary almost completely. In this case fluvial water travels as a surface plume widely over the delta shallows and outflows onto the Gulf of Mexico shelf.

A *halocline,* i.e. a relatively abrupt transition zone, separates the saline and fresh water layers in an estuary. The clearer the halocline, the more stable is the salt-water wedge.

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However, various factors (turbulence of flow, internal waves, convective instability, etc.) cause saline water jets into the upper hyposaline layer. Such uni-directional transport is called *entrainment* and the mixing mode itself is called *stratified with entrainment*. According to various assessments, the proportion of entrainment can reach 50 to 70% of total mixing volume.

If external forcing becomes too intensive, destruction of the interface occurs and intensive mixing starts; this is usually due to tidal motions. Estuarine circulation is then dependent on river flow strength, wind stress, and horizontal pressure gradients. Numerical modeling experiments show that circulation intensity depends on river discharge to a lesser degree than horizontal pressure gradients, controlled to a great degree by amplitude of tidal motions.

The final stage case of mixing is that of complete vertical homogeneity, when the freshwater component plays a negligible part. It should be noted that SRWI process to a large degree depends on morphometric features of the IWA. Therefore we may distinguish between narrow estuaries where the maximum effect of fluvial factors is expressed, wide estuaries, and estuarine shelf where marine factors predominate (see Figure 1)

Marine type of SRWI starts at the outflow from the intensive mixing zone. First of all it is characterized by a flow discontinuity and formation of local freshened water volumes within saline water. These pass through three successive stages: formation of tongues, formation of lenses and bachground freshening. *Tongues* have an elongated form and are connected to the main water mass by a narrow link (cross-piece). From time to time the cross-piece collapses under the effect of outer forces and a *lens* arises. Therefore tongues and lenses have many common features, specifically very close physio-chemical characteristics. The horizontal scale of tongues and lenses depends on river discharge and varies greatly: from hundreds of meters to hundreds of kilometers. Their thickness ranges from tens of centimeters to tens of meters. The salinity of tongues and lenses can differ very markedly from that of the surrounding sea water (by up to 5‰); this helps to maintain fairly stable frontal interfaces.

As a result of wind driven mixing, currents, and other factors, the lenses are gradually eroded and lose their isolation through mixing with surrounding waters. Consequently a background freshening stage begins when a low salinity plume forms and propagates, depending on the predominant currents and wind direction. Such plumes can reach a significant size. For example, the low salinity plume formed in the eastern pacific by the River Columbia in summer (see Figure 2) extends for more than 500 km in a south-western direction from the river mouth, under the influence of the predominantly northerly wind and surface current. In winter, when the south wind is predominant, the plume turns away to the north, travels close to the shoreline, and occupies a relatively small area.

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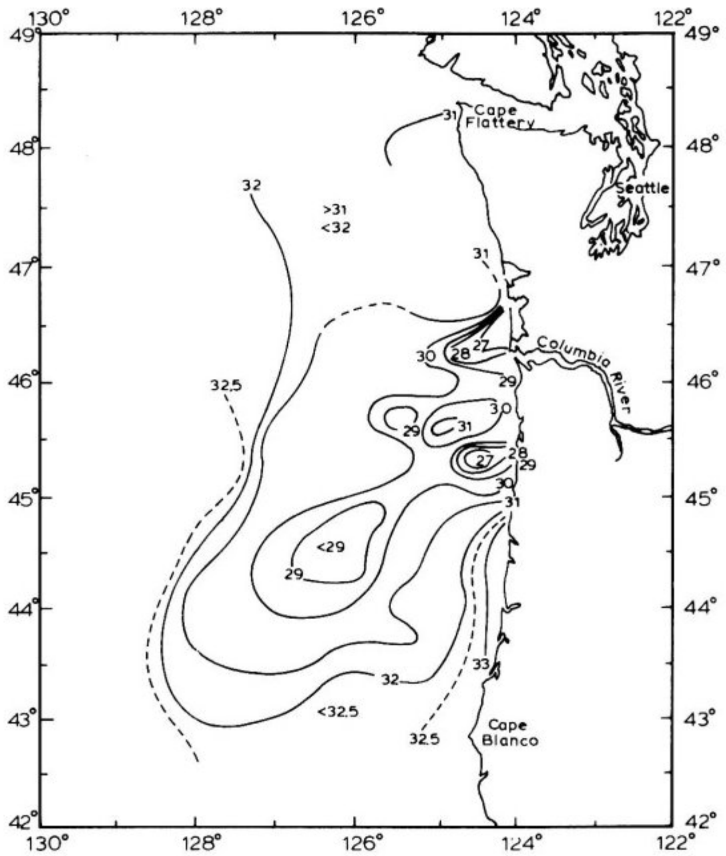

Figure 2. Salinity distribution on the Pacific Ocean surface in summer in area of River Columbia runoff influence. According to Bowden K.F. (1983)

The biggest river in the world, the Amazon, the discharge of which (220 000 m^3 /s) is nearly 17% of global continental flow, is characterized by unique features of SRWI in its mouth. The delta arms of the Amazon estuary are generally 10 to 20 km wide, and 20 to 45 m deep but the delta contains a system of bars which are about only 10 m in depth. Just here intensive mixing of marine and fluvial water occurs, with significant promotion by tides, the height of which is up to 5 m. The zone where two-layer circulation with entrainment and mixing occurs is situated between the most upstream bar and the mouth, its length being about 200 km. Seawater has very little influence upstream of this bar. Further fluvial water transformation proceeds in the ocean. Marine-type interactions include transformation from tongues to lenses. The Guiana Current that passes in a north-western direction along the shelf edge entrains freshened waters, thus preventing formation of a vast freshened water tongue. Consequently the tongue throws itself flat along the shoreline, sometimes reaching as far as the island of Trinidad. During periods of weakening of the Guiana Current, the tongue can cross the flow and form a lens. In some cases such lenses reach a giant size (1400 x 600 km and more) and the distance from the Amazon inlet can be 2500 km. The thickness of the freshened layer in lenses reaches 20 m and they can be maintained for months. Quantitative estimations show that the fluvial water volume required for such lens formation is 150 to 400 km^3.

The formation of mobile frontal zones is an important feature of SRWI. These zones are characterized by significant spatial gradients of the main physical and chemical parameters. Within this three-dimensional spatial zone, a surface coincident with maximum gradient for any parameter (temperature, salinity, etc.) can be traced. This is called frontal surface. Intersection of such a surface with the ocean surface gives what is usually called a *front*. Naturally, in SRWI regions we are mainly concerned with haline frontal zones—the salinity gradient in these can reach 10‰ per 1 km, or more. Distinctive features of these frontal zones are their very complex inner structure, high dynamic activity, considerable space-time variability, and increased biological productivity.

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Biographical Sketches

Valery Nikolaevich Malinin was born in 1948. Having graduated from Sea Academy after adm. Makarov, he succeeded to the speciality of oceanologist. He worked in the Arctic and Antarctic Scientific Research Institute, and the State Hydrological Institute. From 1981 to the present he has been working in the Russian State Hydrometeorological University, where he progressed from teacher to professor. In 1978 he took a Ph.D (Geography) degree and in 1994 a D.Sci (Geography) degree. He has been a professor since 1996. He is the author of 100 printed works, including five monographs and four textbooks, including:

- General Oceanology. Part 1. Physical Processes. (1997), St. Petersburg, RSHU Publ., 342 p. (in Russian),
- Vapor Exchange in the Ocean-Atmosphere System (1994), St. Petersburg, Gidrometeoizdat, 197 p. (in Russian),
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- The Hydrosphere of the Earth (co-author) (2004). St. Petersburg, Gidrometeoizdat (in print). (in Russian),

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His main scientific interests are connected with studying waters of the hydrosphere, the hydrological cycle, climate variation, statistical methods of information analysis, and methods of forecasting hydrological characteristics.

Alexei Vsevolodovich Nekrasov was born in February 1933 in Moscow. He graduated from Leningrad Hydrometeorological Institute (now Russian State Hydrometeorological University) in 1956 and then worked as an oceanographer at the Hydrometeorological Service (in Kamchatka), at the Leningrad Hydrometeorological Institute, Sea Academy after adm. Makarov. From 1982 to the present he has worked at the Russian State Hydrometeorological University. He received his Ph.D (Geography) degree in 1963 and DSc. (Geography) degree in 1977. In 1979 he took a Professor certificate.

He is the author of about 100 printed works including the following monographs and text-books:

- Tidal waves in marginal seas. Leningrad, Gidrometeoizdat, 1975, 247 p. (in Russian);
- Ocean Dynamics. Leningrad, Gidrometeoizdat, 1980, 304 p. (Co-author) (in Russian).
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His principal scientific interests are related to ocean long wave phenomena (tsunami and tides) and prediction of impacts produced by coastal engineering on environmental conditions in near-shore water and land areas.

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